GDR Parameters for Atomic Nuclei Within New Systematics

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Abstract. This work presents new values of giant dipole resonance (GDR) parameters with their uncertainties. Renewed systematics for giant dipole resonance parameters are given. In order to test simplified radiative strength function (RSF) models, the gamma-decay RSF are calculated by the use of renewed GDR parameters and compared with experimental data. It is demonstrated that closed-form approaches with asymmetric shape of the gamma strength provide the most reliable simple method for the γ-decay description.

Introduction

Gamma-emission is one of the most universal channels of the nuclear de-excitation which accompany any nuclear reaction. The photoabsorption and gamma-decay processes can be described by means of gamma-ray (radiative) strength functions [Kopecky, 1998; Capote et al., 2009]. The RSF is involved in calculations of the observed characteristics of most nuclear reactions. They are also used for investigation of nuclear structure (nuclear deformations, energies and widths of the giant dipole resonances, contribution of velocity-dependent force, shape-transitions, etc) as well as for study of nuclear reaction mechanisms.

Dipole electric (E1) gamma-transitions are dominant when they occur simultaneously with transitions of other multiplicities. Isovector Giant Dipole Resonances (IVGDR or GDR) are strongly displayed in E1 gamma-transitions in processes of photo-absorption and gamma decay of the atomic nuclei [Kopecky, 1998; Capote et al., 2009; Berman and Fultz, 1975]. This provides possibility to obtain GDR parameters from investigations of the E1 gamma-transitions. A comprehensive experimental database containing a proper estimate of the accuracy of the GDR parameters is very important in nuclear reaction codes for the reliable modelling of E1 gamma-ray cascades in highly excited nuclei as well as for the verification of different theoretical approaches used for description of GDR resonances.

In this contribution, we present updated values of the GDR parameters with estimates of their uncertainties (one-sigma standard deviation) [Plujko et al., 2010]. The GDR parameters are treated as variables in the least-squares fitting of the calculated total photo-absorption cross sections to the experimental data retrieved from the EXFOR database (available online at http://www-nds.iaea.org/exfor/). Different Lorentzian-type models of E1 strength functions are tested by comparison of experimental data with theoretical calculations using new data base of the GDR parameters.

GDR parameters with uncertainties and systematics

The experimental values of the GDR parameters in cold atomic nuclei are most reliably deduced from photo-absorption data. An extensive compilation of the parameters of Lorentz curves fitted to the total photoneutron cross-section data for medium and heavy nuclei (A > 50) was prepared by Dietrich and Berman [1988]. Additional analysis of experimental data was presented by Berman et al. [1987]. The data from [Dietrich and Berman, 1988] and GDR parameters for light nuclei 12C, 14N, 16O, 27Al and 28Si nuclei were listed in the RIPL-1 database [Kopecky et al., 1998] as well as in the RIPL-3 database [Capote et al., 2009] gamma/gdr-parameters-exp.dat file. If the contribution of photo-proton cross sections to the total photoabsorption cross section is small, then the Lorentzian parameters of the total photo-neutron cross sections in spherical and axially deformed nuclei can be identified with the GDR parameters.
Comprehensive databases of the photonuclear reaction parameters were also presented in [Chadwick et al., 2000]. The photo-proton contribution was included there, but the parameters were obtained without the least-squares fitting to Lorentzian shape. Specifically, those databases listed full width at half maximum (FWHM) data for the largest peak in the photonuclear cross sections, that is, they do not contain explicit information on the GDR components of the damping widths in axially deformed nuclei (i.e., on the deformation splitting of the GDR).

In our contribution renewed systematics for GDR parameters are presented. They were obtained using updated values of GDR parameters and their uncertainties derived from the fitting of the theoretical photoabsorption cross sections to the experimental data for the energies around GDR peak and were used for the calculations of gamma-decay RSF. The theoretical photoabsorption cross section is taken as a sum of the terms corresponding to the GDR excitation and quasi-deuteron photodisintegration. The GDR component of the photoabsorption cross section is calculated within a standard Lorentzian (SLO) model as well as within a simplified version (SMLO) of the modified Lorentzian approach MLO1. Detailed description of the updated GDR parameter data-base is given in [Plujko et al., 2010].

New values of GDR parameters and their uncertainties were used to obtain renewed systematics in the following forms (in units of MeV):

\[ \bar{E}_r = \frac{a_1}{A^{1/3}} + \frac{a_2}{A^{1/6}}, \]  

\[ \bar{E}_r = a_1(1 - I^2) \cdot A^{-1/3} \sqrt{I + a_2 A^{-1/3}}, \quad I = (N - Z) / A; \]  

\[ \Gamma_r = b_1 E_r^{1.91}, \]  

\[ \Gamma_r = b_1 E_r + b_2 E_r \beta^2 - b_3 E_r^{2}, \]  

\[ S_r = \frac{\pi}{2} \sigma_r \Gamma_r = c_1 \cdot 60 \cdot N \cdot Z / A, \quad [mb \cdot MeV], \]  

where \( E_r \) and \( \Gamma_r \) are GDR energy and width respectively, average GDR energy \( \bar{E}_r \) is equal to \( E_r \) for spherical nuclei and \( \bar{E}_r = (E_1 \sigma_1 + E_2 \sigma_2) / (\sigma_1 + \sigma_2) \) for axially deformed nuclei [Berman and Fultz, 1975], \( \sigma_{1,2} \) - cross section values in the first and second peak respectively, \( E_2^t \) - energy of the first collective \( 2^+ \) state, \( \beta_2 \) - parameter of quadrupole deformation, \( N \) and \( Z \) - numbers of neutrons and protons in nuclei with mass number \( A \). Table 1 presents values of fitting coefficients and their uncertainties for systematics (1)-(5) within SLO and SMLO(MLO1) models.

The comparisons of the mean GDR energies and GDR widths with different systematics within SLO model are presented in Figure 1. As one can see from Figure 1, GDR energies and GDR widths within renewed systematics in general agree with previous results [Berman and Fultz, 1975; Carlos et al., 1974] for the middle-weight and heavy atomic nuclei. Differences in range with \( A < 50 \) can be ex-

<table>
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<th>Eq.</th>
<th>Parameters</th>
<th>SLO</th>
<th>SMLO(MLO1)</th>
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<tr>
<td>(1)</td>
<td>( a_1 )</td>
<td>17.79(13)</td>
<td>18.03(13)</td>
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<td></td>
<td>( a_2 )</td>
<td>26.45(60)</td>
<td>26.50(63)</td>
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<td>(2)</td>
<td>( a_1 )</td>
<td>156.47(68)</td>
<td>155.35(67)</td>
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<tr>
<td></td>
<td>( a_2 )</td>
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<td>14.64(17)</td>
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<td>(3)</td>
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<td>0.025348(4)</td>
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<tr>
<td>(4)</td>
<td>( b_1 )</td>
<td>0.3351(10)</td>
<td>0.3465(11)</td>
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<tr>
<td></td>
<td>( b_2 )</td>
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<td>0.0279(53)</td>
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<tr>
<td></td>
<td>( b_3 )</td>
<td>0.325(10)</td>
<td>0.321(11)</td>
</tr>
<tr>
<td>(5)</td>
<td>( c_1 )</td>
<td>1.191(2)</td>
<td>1.22(2)</td>
</tr>
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</table>

Table 1. Values of parameters for systematics (1)-(5) and their uncertainties (in the brackets, values of parameter uncertainties correspond to the last digits of the parameter values) within the SLO and SMLO(MLO1) models.
Figure 1. Mean GDR energies (a): solid line - parameters obtained within systematics (1), crosses - parameters from systematics (2), dashed curve - parameters from systematics of Berman and Fultz [1975; and GDR widths (b): solid line - parameters obtained within systematics (3), crosses - parameters from systematics (4), dashed curve - parameters from systematics of Carlos et al. [1974]. Renewed data fitting is shown with open circles. Calculations were performed within the SLO model.

Figure 2. Ratio of renewed GDR energies (a) and GDR widths (b) within SMLO(MLO1) and SLO models.

plained by ignorance in previous studies of cross sections of the photo-charged-particle reactions which give important contribution to $\sigma(\gamma,\text{abs})$. All the experimental data sets for each nucleus were used in the calculations.

Figure 2 demonstrates ratio of renewed GDR energies (a) and GDR widths (b) within SMLO(MLO1) and SLO models. It can be seen that the SMLO and SLO parameters are as a rule in agreement.

Verification of simplified RSF models

Different phenomenological models with Lorentzian-shape expressions can be used for RSF description [Kopecky, 1998; Capote et al., 2009]: Standard Loretzian (SLO), Enhanced Generalized Loretzian (EGLO), Generalized Fermi liquid (GFL) model, modified Loretzian (MLO) with different semi phenomenological expressions for the damping width (MLO1, MLO2, MLO3) and simplified version of the MLO1 model (SMLO). SMLO models differs from MLO1 one with simplified expression for the damping width. There two types of RSF: photo-exciatton strength function $f^P$ (related to the cross-section for gamma-ray absorption) and gamma-decay strength function $f^H$ (determines the average radiative width of the gamma-decay). On the SLO model expression for the
damping width is energy-independent. For the gamma-decay RSF within the EGLO and GFL models, damping width are functions of the excitation energy (temperature) of the nucleus, whereas within MLO(SMLO) models, there is also additional dependence of the RSF expressions on the excitation energy (see [Capote, 2009]).

In order to test RSF models given above, the gamma-decay radiative strength functions are calculated by the use of renewed GDR parameters and compared with experimental data. In case if for some nuclei GDR parameters were absent, they were estimated from systematics (1), (3), (5) in the following way: \( E_1 = \overline{E}_r / (1 + \alpha_2), \quad E_2 = \overline{E}_r / (1 - \alpha_2 / 2), \quad \Gamma_{1,2} = \Gamma_r (E_{1,2}), \quad \sigma_1 = \sigma_r / 3, \quad \sigma_2 = 2 \sigma_r / 3, \quad \alpha_2 = \sqrt{5/4 \pi} \beta_2, \) where \( \beta_2 \) is effective parameter deformation derived from quadrupole momentum in approximation of axially deformed nuclei (file deflib.dat packed in gamma-strength-analytic.tgz, section GAMMA on http://www-nds.iaea.org/RIPL-2/). The SMLO parameters were used for RSF calculations within different MLO models (MLO1, MLO2, MLO3), and for other models (SLO, EGLO, GFL) GDR parameters of SLO model were applied (as it was assumed by authors of the corresponding models). Different variants of MLO model give similar trend for photoabsorption cross sections. Therefore, in the figures below we present only results of the MLO1 calculations.

Fig. 3 shows gamma-decay RSF for \(^{148}\)Sm and \(^{150}\)Sm within different models as function of gamma-ray energy in comparison with experimental data. Calculations were performed using Back-Shifted Fermi gas model for the temperature determination (see paragraph B, section 8 in [Capote et al., 2009]).

As one can see from Fig. 3, in the low-energy region considered models of the RSF (EGLO, GFL, MLO1(SMLO)) describe the experimental data much better than the SLO model, which predicts a vanishing strength function at zero gamma-ray energy.

Table 2 presents the ratio \( \sum_{i=1}^{n} \chi^2_i / \sum_{i=1}^{n} \chi^2_i (\text{SLO}) \) of chi-square deviations of the theoretical RSF of gamma-decay \( \tilde{f}(E_\gamma) \) from experimental data for \( n \) nuclei. The \( \chi^2_i \) values for nuclei \( i \) were calculated as \( \chi^2_i (\text{model}) = \sum_{j=1}^{n_{E_\gamma}} \left( \tilde{f}_\text{exp} (E_{\gamma,j}) - \tilde{f}_\text{model} (E_{\gamma,j}) \right)^2 / \Delta f^2 \) \( H \), where \( n_{E_\gamma} \) - number of \( E_\gamma \) values. As one can see from the Table 2, strength functions within EGLO, GFL, MLO models give better results then the SLO one. It enables us to conclude that asymmetric shape of the RSF gives better agreement with the experimental data at least in approximation of axially-deformed nuclei which is adopted in presented calculations. The MLO and GFL models give the best agreement with experimental data for heavy nuclei.

**Figure 3.** The dependence of gamma-decay dipole RSF\( (\tilde{f}) \) within different models on gamma-ray energy for \(^{148}\)Sm (b) and for \(^{150}\)Sm (a). Excitation energy \( U = S_n \). The experimental data are taken from [Melby at al., 2001; Agvaanluvsan et al., 2004] (a) and [Sukhovoj et al, 2005, 2007](b).
Table 2. The average $\sum_{i=1}^{n} x_i^2$(model)/$\sum_{i=1}^{n} x_i^2$(SLO) ratio of chi-square deviations of the theoretical RSF of $\gamma$-decay from experimental data: $n = 39$ for data from [Melby et al., 2001; Agvaanluvsan et al., 2004], $n = 38$ for data [Sukhovoj et al., 2005, 2007], $n = 53$ for data [file kopecky.dat, section GAMMA on http://www-nds.iaea.org/ripl/] [Kopecky, 1998].

<table>
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<th>Exp.Data</th>
<th>$n$</th>
<th>EGLO</th>
<th>GFL</th>
<th>MLO</th>
<th>SMLO</th>
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<tr>
<td>[Melby et al., 2001; Agvaanluvsan et al., 2004]</td>
<td>39</td>
<td>0.112</td>
<td>0.104</td>
<td>0.088</td>
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<tr>
<td>[Sukhovoj et al., 2005, 2007]</td>
<td>38</td>
<td>0.256</td>
<td>0.233</td>
<td>0.198</td>
<td>0.192</td>
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<td>[Kopecky, 1998]</td>
<td>53</td>
<td>0.128</td>
<td>0.118</td>
<td>0.191</td>
<td>0.189</td>
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As one can see from the Table 2, strength functions within EGLO, GFL, MLO models give better results then the SLO one. It enables us to conclude that asymmetric shape of the RSF gives better agreement with the experimental data at least in approximation of axially-deformed nuclei which is adopted in presented calculations. The MLO and GFL models give the best agreement with experimental data for heavy nuclei.

Conclusions

Renewed systematics for GDR parameters are obtained and used for testing of different simplified RSF models. The overall comparison of the calculations and experimental data shows that the EGLO and MLO (SMLO) approaches of the RSF provide a unified and rather reliable simple method to estimate the dipole RSF both for $\gamma$-decay and for photoabsorption over a relatively wide energy interval ranging from zero to slightly above the GDR peak.

Reliable experimental information is needed for more accurate determination of the dependence of the RSF on gamma-ray energy and excitation energy (temperature) of the nucleus, so that the contributions of the different mechanisms responsible for the damping of the collective states can be further investigated. This should also provide a means of reliable verification of the closed-form models of the E1 RSF.

References


